

1 Micro Cogeneration Technology

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1.1 Defining Micro Cogeneration

The principle of cogeneration has long been known. As early as the first decade of the 20th century, a number of cogeneration units were already supplying heat and electricity to houses and companies. Cogeneration, or combined heat and power production (CHP), is “the process of producing both electricity and usable thermal energy (heat and/or cooling) at high efficiency and near the point of use” (WADE 2003). It thus incorporates three defining elements: 1) the simultaneous production of electricity and heat; 2) a performance criterion of high total efficiency; and 3) a locational criterion concerning the proximity of the energy conversion unit to a customer.

While the discussion on micro cogeneration, or micro CHP, has only recently gained momentum, the technological roots of micro cogeneration go back to the early development of steam and Stirling engines in the 18th and 19th century, respectively. Today, several technologies exist that are capable of providing cogeneration services, such as reciprocating engines, gas turbines, Stirling engines, and fuel cells. But, in principle, the exhaust heat from any thermal power plant, such as gas combined-cycle power plants or coal power plants, can be used for cogeneration applications.

Advances in the technology, as well as a general trend towards smaller unit sizes of power plants, have led to an increased interest in small CHP units, with the hope of ultimately developing units that can provide electricity and heat for individual buildings. This is what we call micro cogeneration which we define as the

simultaneous generation of heat, or cooling, energy and power in an individual building, based on small energy conversion units below 15 kW_{el}.

Whereas the heat produced is used for space and water heating inside the building, electricity produced is used within the building or fed into the public grid.

Opposed to, for example, the EU cogeneration directive, according to which micro cogeneration is defined as “a cogeneration unit with a maximum capacity below 50 kW_{el}” (EU 2004), we restrict the definition of micro cogeneration to systems below 15 kW_{el} for the following reasons. Firstly, these systems are clearly systems for use in single-family dwellings, apartment houses, small business enterprises, hotels, etc., which can be distinguished from systems supplying heat to a district or neighborhood (i.e. district heating systems). Secondly, systems in this small power regime substantially differ from larger ones with respect to electricity distribution, ownership models, restructuring of supply relationships, and consumer behavior. Also, compared to conventional CHP, based on district heating, no additional heat distribution grid is required. Systems below 15 kW_{el} can be directly connected to the three-phase grid. Moreover, the barriers all CHP systems have to face are more pronounced in the case of such small systems.

As shown in Sect. 2.2, taking an integrated perspective, the innovation of micro cogeneration combines a set of novelties in a number of dimensions. At first sight, though, micro cogeneration often appears as a purely technical innovation. The obvious aspect of novelty is the introduction of a new machine, with new functionalities and different connections to other technical components of the electricity and heat supply system. In this chapter, we will look at the different technical components of a micro cogeneration plant as well as the technologies available for micro cogeneration purposes.

The technological core of micro cogeneration is an energy conversion unit that allows the simultaneous production of electricity and heat in very small units. In addition to this core, further technology components are

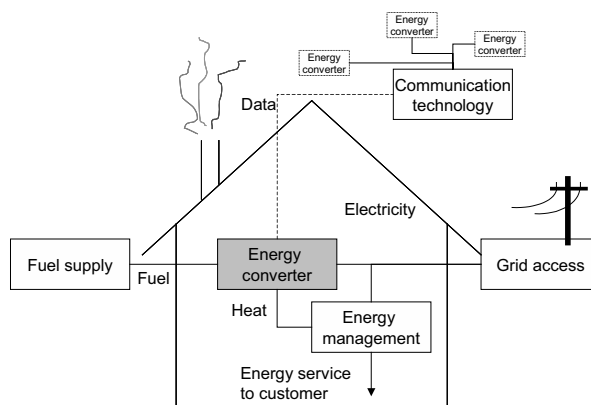


Fig. 1.1. Technological components of a micro cogeneration system

involved in a micro cogeneration system (Fig. 1.1), such as well-developed grid access, including possible metering and control devices. In the remainder of this chapter, the various technological components of such a system will be described in detail.

1.2 Conversion Technologies

A conversion technology serves to convert chemical energy that is stored within a fuel into “useful” forms of energy, i.e. electricity and heat. A number of different conversion technologies have been developed which have domestic CHP applications (Fig. 1.2). The conversion process can be based on combustion and subsequent conversion of heat into mechanical energy, which then drives a generator for electricity production (e.g. reciprocating engines, Stirling engines, gas turbines, steam engines). Alternatively, it can be based on direct electrochemical conversion from chemical energy to electrical energy (i.e. fuel cell). Other processes include photovoltaic conversion of radiation (e.g. thermo photovoltaic devices) or thermoelectric systems.

In principle, most conventional cogeneration systems can be down-scaled for micro cogeneration applications. However, some of them have yet to be successfully implemented for very small applications. Micro gas turbines, for instances, have only been developed with capacities above $25 \text{ kW}_{\text{el}}$ and are thus not categorized as micro cogeneration technologies according to our definition.

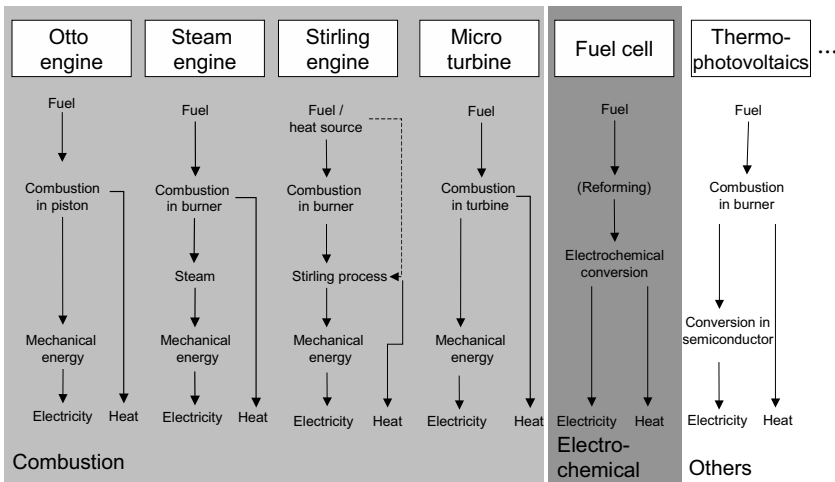


Fig. 1.2. Cogeneration technologies and conversion steps

1.2.1 Reciprocating Engines

Reciprocating engines are based on conventional piston-driven internal combustion engines. For micro cogeneration applications, typically, spark ignition (Otto-cycle) engines are used, comparable to those used in automobiles. In an Otto engine, a fuel, for instance natural gas, is mixed with air and compressed in a cylinder. This mixture is then ignited by an externally supplied spark. The now hot, expanding gas moves a piston, thereby causing the crankshaft to rotate. The mechanical energy produced by this combustion is then used to drive a generator. The exhaust heat as well as the heat from the lubricating air cooler and the jacket water cooler of the engine are recovered using heat exchangers, and then supplied to the heating system.

Reciprocating engines operate with less excess air compared to gas turbines. This leads to higher combustion temperatures, causing thermal NO_x production, due to the oxidation of the nitrogen contained in the air. There are two possibilities to reduce the amount of NO_x released. The engine can be operated in a lean mode, i. e. with excess air, so that reaction temperatures of the reaction are lowered. The second option is to operate the system almost stoichiometrically (i. e. with an air/fuel ratio $\lambda = 1$) and to use a three-way catalyst.

The electrical efficiency of reciprocating engines, defined as net electrical energy output divided by natural gas input, depends strongly on the electrical capacity of the system (Fig. 1.3). At sizes below $15 \text{ kW}_{\text{el}}$, efficiency generally does not exceed 26 %. Thermal efficiency depends on the system and its level of heat integration (e.g., whether condensing heat

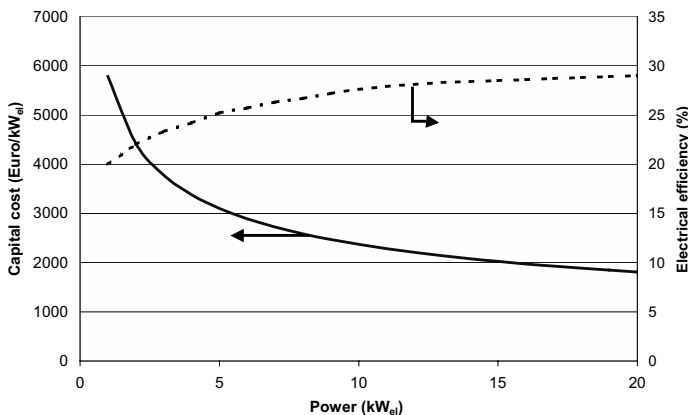


Fig. 1.3. Capital cost and electrical efficiency of reciprocating engines as a function of the size of the system (Source: ASUE 2001)

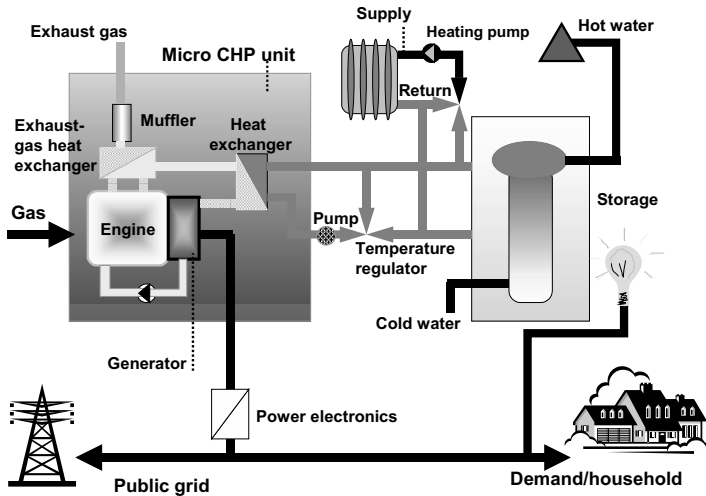


Fig. 1.4. Principle components of a reciprocating engine system (adapted from Ecopower)

is used). Combined electrical and thermal efficiency (total efficiency) varies between 80 and well above 90 %. Similar to electrical efficiency, capital costs per kW_{el} depend on the electrical capacity of the system. A significant decline of capital costs (scale effect) can be observed particularly as systems reach the $10 \text{ kW}_{\text{el}}$ range (see Chap. 4).

Current Developments

Reciprocating engines are commercially available and produced in large numbers by a variety of companies worldwide. The market leader is the Germany-based company Senertec. The Senertec model – called Dachs (“badger”) – generates $5.5 \text{ kW}_{\text{el}}$ and a thermal power of 14 kW (Fig. 1.5). It achieves 25 % seasonal electrical efficiency and thermal efficiencies above 80 % (depending on the building, over 90 % when using a condenser). As of fall 2004, Senertec had sold 10,000 of these models.

Other companies providing micro cogeneration units include Power Plus (recently purchased by the boiler company Vaillant), with its $4.7 \text{ kW}_{\text{el}}$ Ecopower module, capable of modulating its capacity, and the US-based Vector CoGen (5 and $15 \text{ kW}_{\text{el}}$), using a Kawasaki combustion engine. The latter is currently optimized for series production. According to the product specifications, Vector CoGen units achieve electrical efficiencies of around 28 to 34 % and total efficiencies between 70 and 79 %. In Japan, the companies YANMAR, Sanyo and AISIN also develop reciprocating engine based power stations.



Fig. 1.5. Senertec Dachs (left) and PowerPlus Ecopower (right): examples of reciprocating engine micro cogeneration for apartment houses and small commercial enterprises (Sources: Senertec and Ecopower)

An interesting development for single-family house applications is Honda's small 1 kW_{el} system named Ecowill (Fig. 1.6), which was developed jointly with Osaka Gas and other companies. Honda's cogeneration unit combines the GE160V – the world's smallest natural gas engine – with a lightweight generation system. The system is based on a $\lambda = 1$ Otto engine, with a three-way catalyst and oxygen feedback control to reduce the quantity of NO_x emissions. Osaka Gas distributes this system and has already sold more than 10,000 units in 2004 (see Chap. 13).



Fig. 1.6. Honda Ecowill micro cogeneration engine (Source: ASUE)

1.2.2 Stirling Engines

Unlike spark-ignition engines, for which combustion takes place inside the engine, Stirling engines generate heat externally, in a separate combustion chamber. In the Stirling engine, developed in 1816 by Robert Stirling, a working gas (for instance helium or nitrogen) is, by means of a displacer piston, moved between a chamber with high temperature and a cooling chamber with very low temperature. On the way from the hot to the cold chamber, the gas moves through a regenerator, consisting of wire, ceramic mesh or porous metal, which captures the heat of the hot gas and returns it to the gas as the cold gas moves back to the hot chamber.

Stirling engines can be designed in different configurations, distinguished by the position and number of pistons and cylinders and by the drive methods (cinematic and free-piston) (Educogen 2001). The mechanical energy of the Stirling engine is used to drive a generator.

Due to the fact that fuel combustion is carried out in a separate burner, Stirling engines offer high fuel flexibility, in particular with respect to bio-fuels, and, because of the continuous combustion, lower emissions. In principle, other heat sources, such as concentrated solar irradiation, can be used. Companies such as Solo and Sunmachine have developed parabolic mirrors for that purpose.

Stirling engines have the potential to reach high total (electrical plus thermal) efficiencies. Their electrical efficiencies, however, are only moderate. So far, 20 % seasonal average efficiency has been achieved in larger systems, with a predicted > 24 % for future models. Small Stirling engines are designed for low cost; consequently, they achieve lower electrical efficiencies than larger units, typically around 10 to 12 %.

Current Developments

Stirling engines are in between the pilot and demonstration phases and marketing. There are still field trials being carried out; but initial commercial products are already defined and on the verge of series production. The New Zealand-based company WhisperTech is developing a Stirling engine called WhisperGen, with a capacity of up to 1.2 kW_{el} and 8 kW of heat (Fig. 1.7). In the WhisperGen, four sets of piston cylinders are put in an axial arrangement. The British utility Powergen, part of Germany's E.ON, has ordered 80,000 WhisperGen power stations, due to be delivered by mid 2005. A prerequisite for this is the establishment of series production facilities. As Stirling engines require very precisely produced components, the scale-up from small-scale to series production presents a considerable challenge.



Fig. 1.7. Example of small ($\approx 1 \text{ kW}_{\text{el}}$) Stirling engine micro cogeneration: WhisperTech

MicroGen markets a linear free-piston Stirling engine with $1.1 \text{ kW}_{\text{el}}$. MicroGen anticipates that, by 2007, series production will be launched. EnAtEc micro-cogen B.V., from the Netherlands, is in the stage of field-testing its 1 kW_{el} unit, with an electrical efficiency of 10 %. The Swiss company powerbloc GmbH is focusing its efforts on a $1.1 \text{ kW}_{\text{el}}$ Stirling engine.

With respect to systems above 1 kW electrical capacity, the German companies Solo, Mayer&Cie. and Sunmachine have been developing Stirling machines. The Solo engine has sold 30 units up until the middle of 2004 (Fig. 1.8). Solo and Sunmachine are also experimenting with wood pellet burners and solar concentrators.

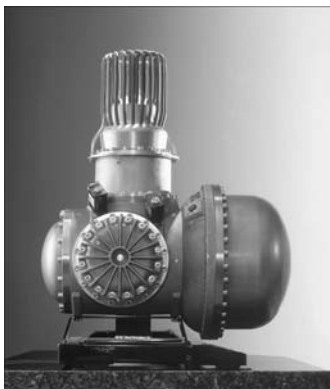


Fig. 1.8. Examples of larger ($\geq 3 \text{ kW}_{\text{el}}$) Stirling engine micro cogeneration: Sunmachine (left) and Solo (right)

1.2.3 Fuel Cells

A fuel cell converts the chemical energy of a fuel and oxygen continuously into electrical energy. Typically, the fuel is hydrogen. The energy incorporated in the reaction of hydrogen and oxygen to water will be partially transformed into electrical energy (Pehnt 2002).

The “secret” of fuel cells is the electrolyte, which separates the two reactants, H_2 and O_2 , in order to avoid an uncontrolled, explosive reaction. Basically, the fuel cell consists of a sandwich of layers that are placed around a central electrolyte: an anode at which the fuel is oxidized; a cathode, at which the oxygen is reduced; and bipolar plates, which feed the gases, collect the electrons, and conduct the reaction heat (Fig. 1.9). To achieve higher capacities, a number of single fuel cells can be connected in series. This is called a fuel cell stack.

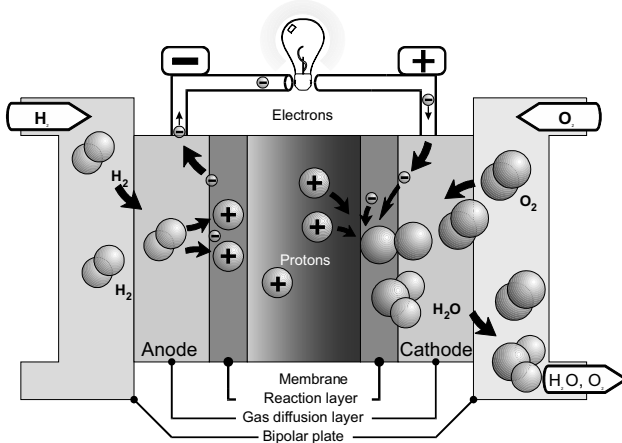


Fig. 1.9. Basic construction of a fuel cell-example Polymer Electrolyte Fuel Cell

Fuel cell micro cogeneration units are either based on Polymer Electrolyte Fuel Cells (PEFC; also Proton Exchange Membrane Fuel Cell, PEMFC), using a thin membrane as an electrolyte and operating at about $80^\circ C$, or Solid Oxide Fuel Cells (SOFC), which are high-temperature fuel cells working at $800^\circ C$. Recent efforts have been working toward the development of high-temperature molten carbonate fuel cells for this low-power segment.

Typically, natural gas is the available fuel for micro cogeneration applications. It mainly consists of the hydrogen-containing methane (CH_4), which is converted into hydrogen in a so-called reforming reaction. This takes place either in a separate device, the reformer, or, as in the case of high-temperature fuel cells, inside the stack (internal reforming).

Taking natural gas as the dominant fuel for fuel cells: In the short- and medium-term perspective, low temperature fuel cells (Proton Exchange Membrane Fuel Cells, PEMFC) in the low-power range may reach seasonal electrical efficiencies on the order of 28 to 33 %; in the long-term it is possible to achieve up to 36 % for domestic systems. However, it is so far unclear whether fuel cell systems can achieve the same thermal efficiencies as promised by the competing technologies. This is due to the fact that the heat cannot be extracted at well-defined points in the system, but rather at many dispersed heat sources, leading to greater measures being required for insulation and heat exchange.

Current Developments

In the last decade, considerable efforts have been made to further develop this technology, particularly in terms of mobile applications. However, fuel cells are not yet commercially available for micro cogeneration applications. Here, both R&D activities and initial field trials are being carried out. Some companies recently had to announce that further R&D is required before their systems can become commercially attractive, with acceptable longevity, technical performance, and system cost.



Fig. 1.10. Examples of fuel cell micro cogeneration: Sulzer Hexis (left), Vaillant (right) (Sources: Sulzer Hexis, EWE AG)

Among the most advanced companies in this sector are Sulzer Hexis, marketing a 1 kW_{el} SOFC system with electrical efficiencies between 25 and 30 %, which is currently being field-tested with more than 100 test units and further developed for series production, and Vaillant, which integrates a Plug Power PEMFC stack into a heating system with

capacities of $4.6 \text{ kW}_{\text{el}}$ and 7 kW_{th} . The latter system is currently being field-tested. IdaTech, together with RWE Fuel Cells and Buderus, is developing a $4.7 \text{ kW}_{\text{el}}$ PEMFC system, and European Fuel Cell GmbH is planning the field-testing of a $1.5 \text{ kW}_{\text{el}}$ PEMFC system. The target electrical efficiency of these systems is above 30 %; some fuel cell manufacturers even anticipate 35 %. As seasonal efficiencies, 32 % seems more likely for micro cogeneration systems. From 2004, the time perspective until readiness for marketing is about 8 to 10 years.

It is interesting to see that most fuel cell developers have been co-operating with major boiler manufacturers to ensure a broad market in the heating sector (see Chap. 7).

1.2.4 Other Technologies

A number of other technologies for micro cogeneration energy conversion are currently under development. Among the more advanced concepts, machines based on Rankine steam cycles are being developed. The Rankine cycle is the ideal prototype for steam engines in use today. Various companies, such as the Australian Cogen Micro with a $2.5 \text{ kW}_{\text{el}}$ system, Energetix' Inergen system with a 1 kW_{el} generator, Climate Energy LCC, or the Baxi Group are pursuing this path, using different types of expanders for the steam, such as free-piston engines, scroll expanders, or reciprocating engines, and different types of working fluids, such as steam, organic substances, or two-phase mixtures of steam and water. However, none of these products is commercially available yet.

One advanced example of a Rankine type engine is the SteamCell, developed by the German company Enginion. In the SteamCell, feed water is compressed, heated with a compact burner, and transformed into steam, which then drives an innovative piston engine (Fig. 1.11). Following the expansion, the steam condenses and flows back into the tank. The SteamCell has a rated electrical power of $4.6 \text{ kW}_{\text{el}}$ and a target electrical efficiency of 17 %. Field tests are planned for 2005, with forecasted market introduction by 2006.

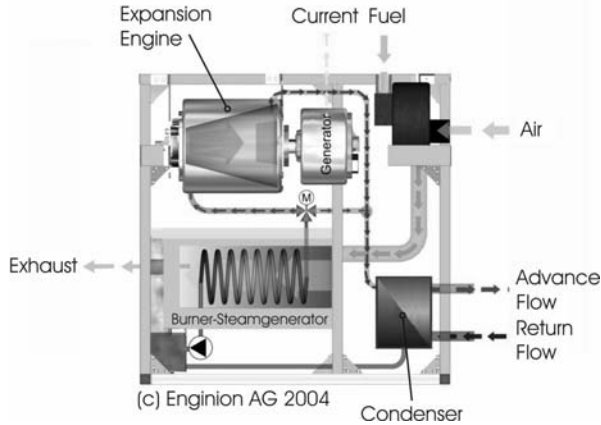


Fig. 1.11. Principles of the steam expansion engine (Source: Enginion)

Due to the continuous combustion in the burner, the hydrocarbon and carbon monoxide emissions remain very low, whereas nitrogen oxide emissions are determined by the maximum combustion temperature, which is carefully controlled in the system. The external heat supply also offers the possibility of using a variety of fuels.

A similar steam cogeneration system is currently being field-tested by the Germany-based company OTAG. In this system, called “Lion” (3 kW_{el}), steam is produced, injected into a piston from alternating sides, and expanded. The moving linear piston then produces electricity.

Generally, the electrical efficiencies of all Rankine cycle machines are low, on the order of 12 to a maximum of 20 %.



Fig. 1.12. Examples of steam cycle based micro cogeneration systems: Enginion SteamCell (left) and OTAG Lion (right)

There are other technologies, which are not based on electrochemical processes (fuel cell) or combustion engines (reciprocating, Stirling, or steam engine), but rather on semiconductors that convert the waste radiant energy of a heat source directly into electricity by means of a modified photovoltaic cell. This technology, called *Thermophotovoltaics* (TPV), applies low band-gap photovoltaic materials. The system consists of a burner and a ceramic emitter (optionally with a filter), which is heated by the burner and emits light, which is then turned into electricity using a photovoltaic cell.

Several developments are required before TPV systems can be successfully introduced into the market. Particularly, the emitter material must be optimized to match the wavelength range to the cells. Several rare earth materials are currently being investigated for that purpose. Also, solar cell design and fabrication, as well as system engineering, are required to optimize performance. Several research institutions, such as the Colorado based National Renewable Energy Laboratory (NREL), and companies, such as Sarnoff Corporation and Edtek, are developing TPV systems.

Thermoelectric devices also directly convert electromagnetic radiation into electricity. However, they do not apply photovoltaic materials, but instead make use of the fact that pairs of dissimilar conductors, e.g. differently doped semiconductor materials such as Bismuth Telluride, produce a current when there is a temperature gradient between them. California based Hi-Z Technology, Inc. developed a 1 kW_{el} thermoelectric generator to generate electricity from the waste heat of engines (e.g. Diesel) as a substitute for the truck engine alternator. In principle, thermoelectric technology can also be employed for micro cogeneration purposes. However, both thermophotovoltaic and thermoelectric devices are not expected to enter the micro cogeneration market in the short or medium term.

1.3 Grid Integration, Communication Technology, and Virtual Power Plants

For operation in the context of a larger system, for instance as a “virtual power plant”, effective devices are required for communication between micro cogeneration units and system operator. These devices should support the optimal operation of the cogeneration system by effectively matching the operation of the individual systems with the demands of the user and of the grid operator.

Networking of several micro cogeneration devices is possible on several levels:

- Microgrids that physically connect the micro cogeneration units to several customers without further transferring information between the units, thus forming a more or less independent grid,
- information technologies connecting the micro cogeneration units to a data server, and
- “virtual power plants”, which combine the information technologies with a central management system.

Communication interfaces are currently being developed by several manufacturers, allowing additional features such as web-based control of the power plant, as well as alarm devices, automated data collection and alerts to maintenance companies in case of failures, etc.

With respect to households, similar communication devices could be developed to form energy management systems for a household. Such *home load management* could actively influence loads, depending on external signals (for instance time-dependent electricity rates), defer and prioritize loads, and, ultimately, act as a “home energy broker”, automatically selling to or buying electricity from other customers.

Taking this a step further, the micro cogeneration unit could be externally controlled by a central operator to exploit additional benefits and services. In several projects, such as in the Vaillant field test program, suitable communication pathways for such communication strategies are being investigated. For instance, an easy and cheap method of communication could be unidirectional ripple control technologies, which allow the utility to turn the power plant on or off in periods of peak or low demand. Data management through the internet, Powerline technology, SMS or other forms of bi-directional data flows would be even more advanced.

The concept of communicative networking ultimately leads to the *virtual power plant*. A virtual power plant consists of a number of geographically distributed power generation units – generally decentralized and low electrical capacity – which are integrated into one larger operational unit by means of a joint control and operator interface (Feldmann 2002; Jänig 2002; Stephanblome and Bühner 2002; Arndt and Wagner 2003). The term “virtual” does not refer to the energy flows, but rather to the plant itself, which is not at one location, but is rather dispersed among a number of generators.

Micro cogeneration units can be elements of such a virtual power plant. Often, larger CHP units and renewable electricity generating systems, such

as wind power and photovoltaics, are mentioned in the context of virtual power plants. Generally, the coordinated connection of individual power plants allows for the balancing of fluctuating rates of generation caused by renewable energy systems (wind, solar irradiation) or by fluctuating demand (CHP systems).

Virtual power plants rely on advances in several technological areas to successfully meet customer demand, technical and safety standards, cost pressures, and environmental performance. Particularly, information and communication technologies and a management system are required for successful integration of the respective energy systems. The management system often includes a forecasting tool to anticipate future generation and demand and to better integrate the individual systems. Communication links to external service providers, such as weather forecasts, electricity stock exchanges, and so forth are required if more sophisticated forecasting and optimization are to be realized. Also, optimization and simulation tools may form part of the management system of a virtual power plant.

Possible communication pathways include telephone communication, particularly ISDN and DSL, internet, ripple control, UMTS, and Powerline technology (where electricity lines are used as a communication medium). Low communication costs are often regarded as crucial for the economic viability of virtual power plants (Lewald 2001; Arndt and Wagner 2003). Lewald calculates that, for certain concepts, 10 % of the monthly total cost would be for communication, which does not mirror the additional benefits of virtual power plants.

From an energy-economic point of view, virtual power plants could offer various ways of reducing costs and increasing revenues (Roon 2003):

- *Cost reduction:* On the hand, there are effects related to “clustered interests”, for instance, buying a number of CHP units or service contracts could lead to volume discounts, as well as discounts for the fuel needed. Also, lower interest rates could be offered to larger operators than to individual power plant operators. On the other hand, the integration of several systems into one operational unit could lead to lower O&M costs, due to automatic early-warning systems, or to minimized fuel use (and thus, lower fuel costs), due to optimized operational strategies (e.g. optimized operating points, merit order).
- *Increase of revenues:* CHP products, particularly electricity, can be marketed differently when many systems are pooled, because the specific transaction costs can be lowered and certain regulatory requirements can be fulfilled (e.g., in order to participate in the control

power market, a minimum capacity is required). These options include selling the electricity on spot or regulating energy markets.

With these positive economic aspects of virtual power plants in mind, one should note that the amount of power that can be devoted to commercialization is usually only marginal because, in many cases, the producer's own consumption of the electricity generated is more lucrative than feeding it into the grid, even considering new marketing possibilities. In addition, power generation is combined with heat generation, which has to be used locally. Furthermore, considerable institutional barriers impair the realization of alternative ways of commercialization. Other than with virtual power plants based on larger individual generation units, under present-day conditions, the potentially higher proceeds of connected micro cogeneration plants do not justify the high expense for installation and management of a virtual power plant (Roon 2003).

1.4 Conclusions

In Table 1.1, different conversion technologies are compared on the basis of selected criteria. In addition, Fig. 1.13 depicts the status of market development of the various technologies.

Table 1.1. Characteristics of micro cogeneration technologies

Conversion technology	η_{el}	η_{th}	Noise level	Pollutant emissions	Fuel flexibility	Market availability	Economic viability
Reciprocating engine	20-25	> 85	Medium	Rather high, depending on catalyst/engine technology and maintenance	Medium	Commercially available	Given for certain applications
Stirling engine	10-24 ^{a)}	> 85	Low	Very low to medium ^{b)}	High	Near to market	Cost reduction necessary
Fuel cell	28-35	80-85	Low	Zero (H ₂) to almost zero (hydrocarbons)	Medium	Pilot plants, R&D	High cost reduction necessary
Steam expansion engine	n. a.	n. a.	Low	not yet measured, principally similar to Stirling	High	R&D	High cost reduction necessary

η : efficiency, el electric, th thermal. ^{a)} depending on the Stirling concept

^{b)} depending on the burner type

Whereas *reciprocating engines* are commercially available, produced in large numbers and achieving high electrical and total efficiencies, they suffer from higher exhaust emissions compared to the competing micro cogeneration systems (see Sect. 5.1.2).

Because fuel combustion is carried out in a separate burner, *Stirling engines* offer lower emissions as well as high fuel flexibility, allowing, in particular, for the use of bio-fuels and solar irradiation. Stirling engines have the potential to achieve high total efficiency, though with only moderate electrical efficiency. Smaller Stirling engines have an even lower electrical efficiency and are primarily designed to be low cost.

Fuel cells are still in the R & D phase, with a number of pilot plants currently being tested. They offer the potential benefit of the highest electrical efficiency and almost zero local emissions. Additionally, the high ratio of electrical to thermal efficiency (power to heat ratio) might increase the CHP electricity generation potential, because with given (and limiting) heat demand, more electricity can be produced (see Chap. 4). In the last decade, considerable efforts have been made to further develop this technology. However, it remains unclear whether fuel cell systems can ever achieve a total efficiency equaling those promised by competing technologies. Also, the high capital cost of early product generations remains a major challenge.

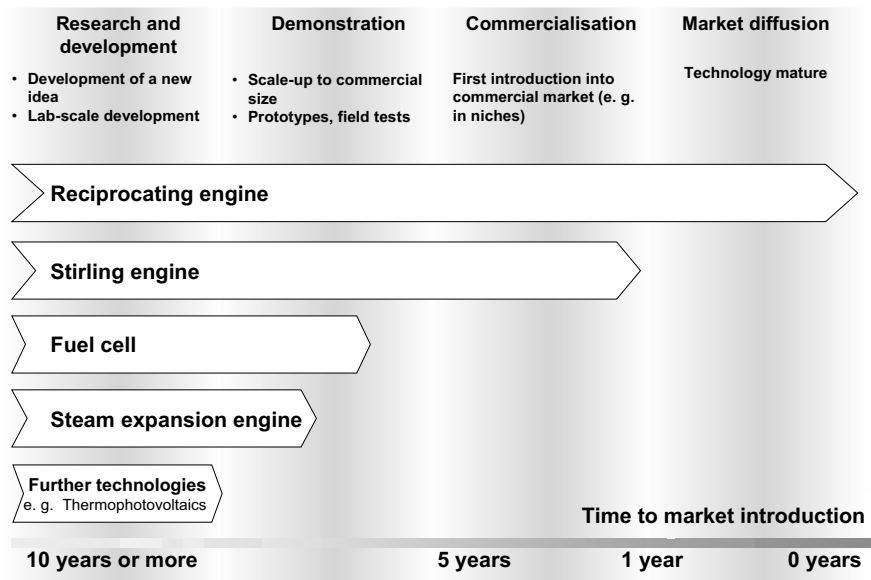


Fig. 1.13. Status of market development of micro cogeneration technologies

Steam expansion machines are still in the R&D phase. Potentially, they offer low emissions and high fuel flexibility, due to their external burner. In addition, some steam engine concepts envision a flexible flow of steam, allowing electricity and heat ratios from approximately 0.3 to pure heat supply. However, the technical demonstration of feasible CHP systems is still awaited and electrical efficiencies are expected to be low. *Other technologies*, such as thermophotovoltaic and thermoelectric systems, are still in the research stage.